Proceedings of the ASME 2015 International Manufacturing Science and Engineering Conference
MSEC2015
June 8-12, 2015, Charlotte, North Carolina, USA

MSEC2015-9392

IMPACT OF ADDITIVE MANUFACTURING ADOPTION ON FUTURE OF SUPPLY CHAINS

Ardeshir Raihanian Mashhadi
Graduate Research Assistant
Department of Mechanical and Aerospace Engineering
University at Buffalo, SUNY
Buffalo, NY 14260
ardeshir@buffalo.edu

Behzad Esmaeilian
Postdoctoral Research Associate
Mechanical and Industrial Engineering
Northeastern University
Boston, MA, 02115
b.esmaeilian@neu.edu

Sara Behdad
Assistant Professor
Department of Mechanical and Aerospace Engineering
Industrial and Systems Engineering Department
University at Buffalo, SUNY
Buffalo, NY 14260
sarabehd@buffalo.edu

ABSTRACT

Although separation of product design from manufacturing capabilities is a major advantage of Additive Manufacturing (AM), the impact of AM is not only limited to the design and manufacturing stages. In addition to the freedom of design such as elimination of design constraints, material saving, and free complexity, AM offers other potential benefits to the manufacturing industry as well. One of the most immediate potentials of AM is the possibility of more efficient logistics. This paper aims at describing the characteristics and requirement of a Supply Chain (SC) as well as the changes AM will bring into the current structure of supply chain. Insights are provided on the transformative effects of AM on traditional businesses, and how these changes impact the configuration of a supply chain. The potential for using simulation tools to evaluate AM supply chain have been discussed. Further, two examples of Agent Based Simulation (ABS) and System Dynamics (SD) have been provided to show the application of simulation models. The ABS results show the possibility of lead time reduction in AM based supply chain. In addition, the SD model illustrates the potential for less 'pipeline' effect in AM compared to traditional supply chain.

1. INTRODUCTION

Although Additive Manufacturing (AM) was first introduced over 30 years ago, until recently, its development occurs in the shadows due to technical limitations, high cost, poor quality, and limited capabilities. However, a dramatic evolution has been initiated in this technology over the past few years. The existing projections illustrate that new discoveries are revealed every week and the progress of AM technology will continue exponentially [1]. According to the 2014 Wohlers Report, the AM market grew close to 35% in 2013, where the annual growth in the three previous years was between 25-30%. The value of all products and services reached $3.07 billion [2].

As the multibillion dollar AM industry keeps evolving, a significant number of companies and even end users have started using 3D printers to produce their products. However, the recent research suggests that AM has not fully satisfied its potential yet. One reason is that the technology has many second-order effects on business operations and economics, that make top management have difficulty in easily accepting this technology [3]. 3D printing is not as cost effective as traditional systems in mass production and traditional manufacturing techniques are still very competitive for the large scale production.

Still many companies are struggling to decide on how to adopt AM technologies. Traditionally, companies only focus on improvement of their internal performance measures, however these days they have started to realize that they have the ability to control more than just their internal activities. One reason for this change paradigm is that in the current business world, customers do not distinguish between a company and its suppliers. Moreover, the performance of one company can directly influence the whole supply chain.

The goal of this paper is to assess supply chain changes associated with AM technology adoption. A review of literature has been conducted to identify the potential impact of AM technology on the configuration of supply chains. Further, the study suggests several analytical tools that can be employed to study the AM supply chain network design problem with the purpose of covering three levels of decisions simultaneously: long-term decisions such as facility location (strategic levels), mid-term decisions such as inventory level (tactical level) and short-term decisions such as production size (operational level).

The remainder of this paper is organized as follow: Section 2 provides a review of literature. Section 3 discusses the changes that AM brings into the current structure of supply chain as well as the characteristics of AM-based production systems. Section 4 describes the new business models resulting from AM. Section 5 introduces two types of simulation models including Agent Based Simulation and System Dynamics that can be used to analyzed AM-based systems. Section 6 provides two examples to show the application of simulation models. Finally, Section 7 concludes the paper and provides future work.

2. BACKGROUND

So far, many techniques and methods have been employed in literature to measure, evaluate and compare the performance of different supply chain configurations. Optimization programming, simulation techniques, statistical analysis, game theory, and life cycle assessment are among those methods.

A Supply Chain Network (SCN) design is concerned with determination of the optimal number, technology, and configuration of facilities in addition to the quantities of raw materials, production, distribution, inventory, and shipments among the established facilities in such a way that customer satisfaction and supply chain values are optimized. The literature dedicated to SCN can be categorized into *two groups:* 1) studies focused on designing forward supply chain, and 2) studies considered both forward network as well as backward network (reverse supply chain, product take-back). The second group is recognized as a closed-loop supply chain.

Although the number of studies looking at AM technologies in terms of cost and technical feasibilities is not limited, there is indeed a lack of research on understanding the supply chain aspects of AM adoption. According to the most recent report provided by the Direct Manufacturing Research Center (DMRC) 'focus on systems innovation and changes along supply chain' has been identified as one of the main research directions for the future of AM technology. A few studies have introduced AM in the supply chain domain. Holmstrom et al. [4] analyzed two approaches to evaluate spare parts supply chain success: 1) locating production facilities in a centralized location and serving the market, 2) distributing production in various national locations close to main markets. They concluded that centralized production is more likely to be profitable. In a similar study, Khajavi et al. [5] discussed the spare parts supply chain for a case study of the F-18 Super Hornet fighter jet and compared four different supply scenarios.

The conclusion was: with the current AM technology, centralized approach is preferable. However, as AM technology matures and AM machines are available with less capital, distributed production becomes practical. However AM based supply chain design should satisfy the compatibility with the traditional supply chain designs because in many cases a combined manufacturing process should be applied in order to cover limitations of AM manufacturing lack of high precision and great surface finishing.

A literature review of the previous studies best reveals that AM-based supply chain has received almost no attention in the literature. In addition, often strategic decisions (e.g. the number of facilities and their locations) have been studied in traditional supply chain design literature, where these strategic decisions have not been fully connected to the tactical and operational decisions such as decisions in the product design, device design and production line levels. Therefore, there is a critical need for developing methods that include all features and changes that AM introduces into the supply chain domain. In the light of mathematical based techniques, the synergy of mathematical models and simulation techniques is viewed as a promising approach for evaluating AM-based supply chains.

3. ADDITIVE MANUFACTURING SUPPLY CHAIN

3.1. Components of Transition from Traditional Supply Chain to AM-Based Supply Chain

This section discusses the characteristics and requirement of a supply chain as well as the changes AM will bring into the current structure.

There are several perspectives through which, AM can be viewed. In the broadest sense, AM can affect the supply chain anywhere, from the most detailed aspect of CAD model within a product design, to logistical decision across the supply chain. At each of these levels there are new opportunities for improvement. And at each of these levels there is a range of changes AM offers to remodel the supply chain. For example, there are different AM processes such as fused deposition modeling, laser sintering and laser melting, each of which brings different information (e.g. time, cost and quality) to the analysis of supply chain. Also, there is a critical linkage between the above mentioned levels. For example the enterprise design should not be considered separate from product design. In fact there is a clear flow of information between them. To determine how AM could benefit the supply chain, executives should examine five principle levels. These five levels (adopted from [6]) are as follow:

- Product Design: product functional requirement and design parameters
- Device Design: production and support equipment
- Production Line Design: logical layout of the devices in the manufacturing lines
- Facility Design: location and layout of the physical facilities

Table 1. Five different levels in supply chain design and the potential changes AM offers in each level

Features of AM-based Supply Chains	
Product Design • Lightweight products • Functional complexity • Freedom of design • Limited number of materials, type of materials	**Production Line Design** • Less consumption of resources • Process automation
Device Design • Laser development • Printers with bigger build chamber • Less setup time	**Facility Design** • Less energy usage and waste • Fixture less manufacturing • Less equipment costs • Fewer and less-skilled operators • Lower inventories
Supply Chain Design •New business models (sell design instead of physical products, New industry of production of AM equipment) • Mass customization/personalization • Less number of suppliers • Demand variation • Less transportation, production close to consumers • Short lead time • Distribution centers that store blueprints rather than physical products	

- Supply Chain Design: the entire manufacturing enterprise including all individual facilities, transportation and supply chain externalities.

Table 1 summarizes five levels of supply chain design and the potential impacts of AM on each level. **The transformative effects of additive manufacturing on traditional supply chains** are summarized under three contexts as follows:

Environmental Context:

- **Lower environmental impacts:** AM offers the potential to limit the number of materials, reduce waste and scrap. The amount of energy used is limited and carbon footprint of a given product will be reduced. In addition, environmental friendly designs will be possible [7].
- **Possibility for waste reduction:** 3D printers would drive companies towards becoming more efficient and reduce waste to a minimum. However, individual consumers using 3D printers at home can be relied upon to be wasteful [8].

Operational Context:

- **Flexibility:** AM industry is significantly flexible both in terms of the type of items that can be manufactured and where the manufacturing takes place [7].
- **Mass customization and print on demand:** AM minimizes cost of low-volume products while makes it easier to manufacture products based on a wide variety of consumers' need and taste levels [9].
- **Reduction in assembly operations:** In many cases several parts can be replaced with one single part with multiple functionalities. Functional integration, implementing several technical functions into a few parts, enables a reduction in the number of assembly operations [10].
- **Lower tooling and fixture-less manufacturing:** Compared to traditional manufacturing systems, AM require less gigs, fixtures and tools [11]. This would decrease setup time in production lines.
- **Automation, fewer working capital and less-expert operators:** new manufacturing automation requires fewer and less-skilled operators.
- **New Business Models:** Business will focus on selling design instead of physical products. Also new industry of production of AM systems and design tools for 3D printers will come to the market [7].

Supply Chain Context:

- **Information flows would increase while material flows decrease:** Designs in form of digital files would move around the globe to be printed in the local market by any printers that meet the design specifications. The same way that internet eliminated the distance in information flow, the AM will reduce the material flows [12]. Distribution centers will store product blueprints and design files on their server farms or 'in the cloud' rather than physical items [13].
- **Local supply chain/ production close to market:** 3D makes it possible to shorten supply chains and reduce the inventories through its close proximity to market and its ability to shorten lead times.
- **Less Logistics, faster supply chain:** since products are manufactured on-site, the need for transportation will decrease and many of the expedited shipments and unnecessary international transportations would be removed [8].

3.2. Impact of Additive Manufacturing on Common Production Systems in Supply Chains

Although the total structure of a supply chain is influenced by AM, its impact on production system is more tangible. To further clarify the impact of AM on supply chain, three most recent production systems including Lean Manufacturing, Agile Manufacturing and Leagile Manufacturing will be discussed.

Lean manufacturing is concentrated on elimination of waste and non-value added activities such as transportation, inventory, motion, waiting time, over production, over processing and defects. Less waste can be achieved through AM technologies as well. Less material, less human effort, less setup time, reduction of transportation and less energy consumptions are among the features that AM can bring into a lean system [14]. Lean manufacturing also comes along with just-in-time strategy in which products are delivered in small quantities with short lead times.

While the lean system is defined as a system with minimum waste, an agile production system is recognized as a system with capability to meet the rapidly changing demand of the market both in terms of the volume and variety of products [15]. Agile system is fairly compatible with make-to-order strategy, where the system is flexible enough to act as fast as possible in the case of change in market demand. The main focus of agile systems is on lead time reduction. AM can be an assist for agile systems as well. AM shifts production more toward consumers. Moreover, it does not require tools, such as jigs and fixtures, which keeps the cycle time short.

However, supply chain managers are under pressure to be both market-responsive and low cost; to be both lean and agile [16]. This system is identified as a leagile supply chain. The main idea is to position a decoupling point and use a different paradigm (lean or agile) on each side of this point. A *decoupling point* is an inventory buffer to meet the discrepancy between actual demand and the sales forecast. In leagile supply chain, the downstream acts based on the agile concept to respond as quickly as possible to a volatile market demand, while the upstream follows the lean concept. Material efficiency, part flexibility, fast customization and less waste makes AM capable to offer leagile supply chain [14].

4. ADDITIVE MANUFACTURING BUSINESS MODELS

Modeling the actual behavior and dynamics of supply chain is a challenge since supply chains are complex, they are subject to frequent changes and often the collaboration and information sharing in the supply chains are not feasible [17]. Adoption of AM technology brings even further changes into the supply chain networks. The following are two changes offered by AM:

- **Variability in market:** The AM industry consists of two distinct markets: professional industrial systems and personal systems. The growth trends of these two markets over the past four years have been significantly different. The unit sales of industrial systems experienced a 37.4% jump from 2009-2010, then declined to 5.6% in 2011 and rose 19.3% in 2012. However, the sales of personal 3D printers rose an average of 346 % each year from 2008 to 2011. The unit sales continued to increase by a slower rate of 46.3% in 2012. The spread of 3D printers among individual consumers (e.g. household, engineering students, educational institutions) reveals the potential changes in the market need from 'actual products' to 'materials' for 3D printers [18]. Furthermore, the flexibility in design introduces high variety in the market and enables customization and personalization.
- **Flexibility in supply:** Unlike the traditional production systems in which highly-integrated supply chains are needed to ensure right parts can be supplied at right time from multiple suppliers, AM makes it possible to order readily available supplies from multiple vendors. The ABS will help us identify the best supply policies based on the variability in the market demand.

Supply chain network should be designed based on new business models offered by AM technology. The integration of the new AM capabilities into existing supply chains is an important area of investigation. Four different business models have been identified.

- **Business Model #1:** Transition from lean to 'leagile' systems. This business model simply implies network configuration based on responsiveness and lead time rather than cost.
- **Business Model # 2:** Increase the structural flexibility (the ability of the supply chain to adapt to fundamental changes). Structural flexibility can be obtained through several strategies such as asset sharing (capacity and inventory) between companies, multiple sourcing, use of multipurpose resources including flexible labor arrangement and flexible machines, outsourcing manufacturing and rapid production of small batches [19]. The AM capabilities facilitate adopting the above mentioned strategies. Examples of strategies can be tested on designing network are:
  - 'Local-for-Local' rather than global sourcing and centralized manufacturing: The AM technology limit the number as well as the type of materials required to build the products. Therefore, it will facilitate asset sharing (in terms of both capacity and inventory).
  - 'Economies of Scope' rather than the 'economies of scale': economy of scope refers to using similar processes to deliver a set of distinct products. The potential questions can be answered are: what is the appropriate level of diversification for each product line? Which products should be covered with each 3D

printer type? Which markets are companies over-serving or under-serving?

- **Business Model # 3:** Virtual supply chain: Transition from inventory-based network to information-based network. As AM continues to grow, the structure of supply chain will move from material-intensive to information-intensive network. Enabling regular people to make physical objects from design models and selling digital blueprints rather than physical products are among the changes that AM brings to the business. Offering 'design blueprints' as a new unit of commerce breaks apart the formerly logistics links in the network and the physical infrastructure of product transportation could be replaced by information links and decentralized manufacturing [20]. Moreover, new business units offering digital design services can be added to the current structure of supply chain network. This business model simply implies network optimization based on information and fund flows rather than just material flows.
- **Business Model # 4** 'cloud manufacturing' businesses that accept design or CAD from clients and make their printers available to consumers will open a new line of business model where the clients can themselves look up which machine is available and submit their parts any time they want.

5. SIMULATION TECHNIQUES TO ANALYZE AM SUPPLY CHAIN

Different techniques and methods can be used to evaluate, measure and analyze the performance of AM-based supply chain. Simulation is one of the well-known methods which is widely-used in supply chain analysis. In this section, we give a brief overview of several useful simulation tools including agent based simulation and system dynamics. Further, we will discuss different dimensions of AM that can be covered through these techniques.

Many analytical models such as optimization, discrete event simulation and hybrid models have been proposed for modelling SCs. Melo et al. [21], and Ding and Liu [22] have provided a detailed review of the literature on these modelling techniques. Although theories and analytical models are helpful in characterizing supply chains, it is important to remember the constraints of existing mathematical models. Theories and mathematical models are mostly designed to predict aggregate results and generalize behaviors (e.g. average behavior of the network) rather than identifying the wide variability in different partners' decisions. In reality, different parties in the supply chain are differentially influenced by various factors and contexts. Most analytical models only take few variables into consideration, and ignore other factors. Furthermore, these models treat systems as not correlated in time, ignoring the dynamic behavior of the entities perform in the supply chain [23]. Therefore, there are some limits to how meaningful such models can be. Although the predictive capability of a model can be enhanced by adding more variables, the additional complexity this gives rise to, often causes policy makers to be unsure about specific interventions and exact sources of change. In addition, models require empirical data to operate and the outputs of such models are only as accurate and robust as the input data. Further, the cost of providing empirical data increases as model complexity increases [24]. To overcome these limitations, this study discusses how simulation models can be used to manage the wide variability in the decisions made by different parties in supply chain network.

5.1. Agent Based Simulation

Among available simulation models, ABS can be of particular help. ABS can capture and model the changes that AM offers in the supply chain and how these changes will influence the structure of the network as well as the decisions made by different organizations in the network. Agent based simulation characterize and model supply chain, where multiple agents form dynamic supply networks and coordinate their production and order planning according to estimation of market demands. Applying simulation, decision makers can identify appropriate interventions and policies that satisfy market requirements quickly with minimum cost and environmental impact. A variety of policies can be investigated using simulation models, to name a few:

- Strategic policies (number of facilities, type of facilities, number of standby suppliers, etc.)
- Production and economic policies (e.g. lead time, automation level, production lot size, inventory safety stock level, pricing decisions, etc.)
- Environmental policies (e.g. tax credits, material flows that minimize CO_2 emission, energy flows, etc.)
- Logistics policies (the optimum distribution of products in a specific retail center, movement of supplies among facilities, etc.)

ABS is a robust tool in modeling complex systems composed of interacting, autonomous agents. Typical agents exhibit behavior (often defined by simple rules), interactions with other agents and the environment, learn from experience and adopt new features and behaviors [25]. With that, ABS can contribute greatly in understanding and analyzing economic and social phenomena. First, considering economics as an application domain, simulation is more rigorous than mathematical modeling [26]. In these simulation models consumers are not regarded as passive targets whose behavior should be changed, but as 'actors' at the heart of the market. Policy makers need to investigate the AM market and co-ordinate their production and order planning as well as logistics decisions. These models can be used to gain insight into the dynamics of AM markets and enhance the understanding of how micro-level (agent-level) manufacturing policies can lead to greater responsiveness in the market.

The diverse decision makers in the supply chain (manufacturers, distributors, transporters, recycling facilities, governmental agencies and final consumers) are represented as ‘agents. The capability to make independent decisions is among the fundamental features of an agent. Each agent could have a set of behavior handled through some primitive decision rules ranging from reactive decision rules providing response to the environment to the higher-level rules providing complex adaptive intelligence [27].

AnyLogic software, Java, and C++ programming can be used to develop the simulation models. The general procedure to build models include: 1) identify agents and players of the market, 2) determine agents’ attributes and behavior, 3) formulate algorithms based on agents' attributes and behaviors, 4) build artificial programs representing agents, 5) implement the algorithms, 6) observe and analyze the system emergent properties.

5.2. System Dynamics Simulation

Another prevailing simulation tool is system dynamics. There are multiple lenses through which to view supply chain problems addressed through SD. In its broadest sense, frequent supply chain problems studies through system dynamics can be focused anywhere from the most detailed aspect of inventory planning decision making within the factory, to strategic decisions across different parties of the supply chain. At each of these levels there are new challenges and opportunities for analysis and improvement. And at each of these levels there is a spectrum of decisions that need to be made.

The use of SD for analyzing supply chain is not something new. In fact, the origin of the supply chain management field refers back to the time when Jay Forrester, an MIT professor and the father of system dynamics field, has introduced Industrial Dynamics, the field that later on was recognized as system dynamics [28]. Holweg and Disney 2005 [29] summarized the evolution of simulation approaches in supply chains modelling into three groups of 1) discrete time simulation, 2) continuous time and 3) control theory. The objectives of these approaches were mainly focused on minimizing inventory holding cost or variance reduction (specially bullwhip related studies) [28].

Several studies have used system dynamics to investigate different aspects of supply chain (e.g. [30]–[32]). System Dynamics is often used in modeling complex systems characterized by casual loops, information feedback and non-linear interactions among many factors. In complex systems, often the cause and effects are not directly related and the causes of difficulty are not necessarily in prior variables but they may even be found in the structure and policies of the system [33].

Model conceptualization, mathematical formulation, model development, and evaluation are the main steps to build and test SD models. System dynamics modelers often use two types of diagram, (1) Casual Loop Diagram (CLD) and (2) Stock and Flow Diagram (SFD). CLDs are used to represent different feedback processes and interactions among variables in form of two types of loop, positive loop and negative loop. While CLD shows the overall structure and scope of the system qualitatively, SFDs are used to model the mathematical mapping behind the system and quantify system’s behavior. Modelers start with mapping the system through CLDs and then convert CLDs to SFDs.

6. APPLICATION

In this section, two examples of simulation models have been developed to show the potential impact of AM adoption on supply chain strategies such as production and inventory planning. While ABS is suitable in terms of capturing individuals’ decision making behavior, SD models are helpful when there are too many interconnected factors in the system. Depending on what the question under study is, each technique provides some potential for analysis.

6.1. Example I: Agent Based Simulation

In this section, an agent based approach has been presented to model two different scenarios of supply chain configuration. A case of manufacturing ten different products using three types of raw material has been considered. Each supplier is responsible for one material type while each product requires a different configuration of raw materials. It has been assumed that the manufacturer keeps raw materials in the inventory instead of storing the whole product. The first scenario shows the traditional supply chain approach (Figure 1). Consumers submit their orders to the nearest retailer. The retailer then transfers the order to manufacturer and this updates the manufacturer’s order list. Manufacturer, for each process cycle, decides whether to produce and ship the product or order new raw materials. This decision is made based on the current inventory level. After production, manufacturer sends the product to retailer and retailer ships it to costumer.

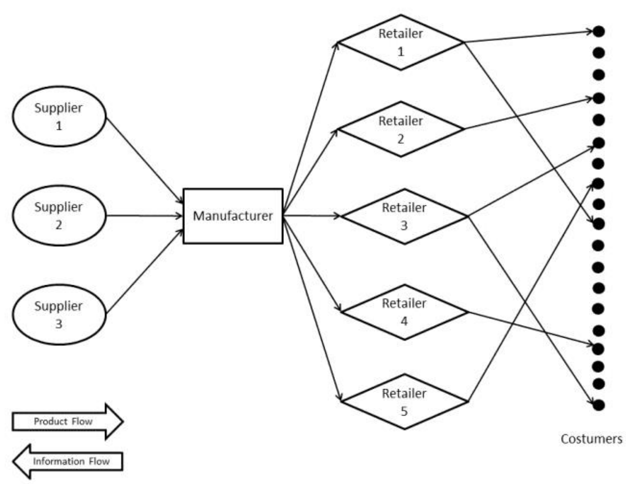


Figure 1. Scenario 1: Classic supply chain configuration: Products are made in manufacturer’s site.

In the second scenario, a modified supply chain configuration has been considered (Figure 2). The manufacturer is not responsible for producing the product but rather providing the retailers with electronic design files and blueprints.

Costumers virtually submit their orders to the manufacturer. Then, the manufacturer updates the corresponding retailer's order list. In this scenario, products are made using additive manufacturing (i.e. 3D printing) on site and by the retailers. Thus, the average processing time will be lower. The production time in the retailer's site is faster than the production time in manufacturer in the previous scenario. Moreover, in this scenario the retailers communicate directly with the suppliers.

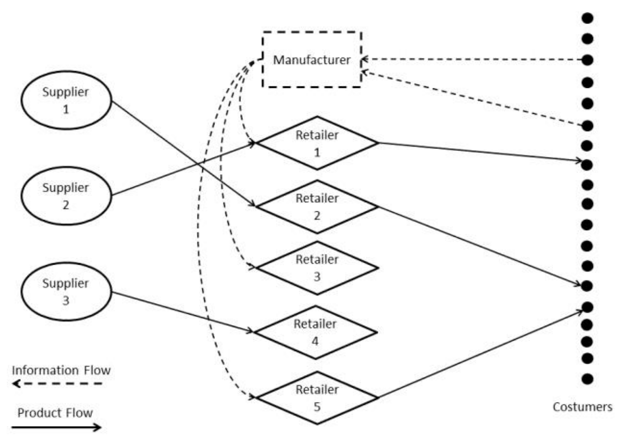


Figure 2. Scenario 2: Modified supply chain configuration: Products are printed in retailers' sites.

The simulation is done using AnyLogic 7. The simulation parameters for both scenarios are listed in Table 2.

Table 2. Simulation parameters in two scenarios

Parameters	Classic SC	AM SC
No. of Manufacturers	1	1
No. of Retailers	5	5
No. of Suppliers	3	3
No. of Costumers	100	100
Processing Time in Mfg. (day)	EXP (Mean 0.5)	0.2
Processing Time in Retailer (day)	0.2	EXP (Mean 0.05)
Processing Time in Supplier (day)	0.2	0.2
Usage Time (Costumer's Frequency to Order)	NORMAL (100, 25)	NORMAL (100, 25)
Initial Inventory (Manufacturer)	30	0
Initial Inventory (Retailer)	0	6
Shipping Time for each Delivery (day)	EXP (Mean 5)	EXP (Mean 5)

Two performance measures have been studied in both scenarios:

- **Inventory Level:** The total number of raw material units held by manufacturer (Classic Model) or the retailers (Modified Model)
- **Lead Time:** The wait time between initiating and receiving the order by consumer

Figure 3 represents the manufacturer's average inventory level over the last 50 orders in the first three thousands time unit of simulation. As seen on the plot, the inventory level rises in response to the huge amount of initial orders. Then it becomes stable at an average of 27 units. The same story happens to each retailer in the second scenario. However the slope and duration of increase and the convergence inventory level are slightly different for each retailer due to the point that they cover different number of costumers and the market share is different for each of them (Figure 4).

Figures 5 compares the lead time in both scenarios. X axis shows the simulation time and Y axis represents lead time (days) for the last order. As shown, lead time is shorter in the modified supply chain due to higher overall inventory level in the system and direct communication of retailers with suppliers. After 3000 cycles, the average lead time in the classic supply chain is 10.88 days, while it is 5.1 days in the modified supply chain (AM supply chain).

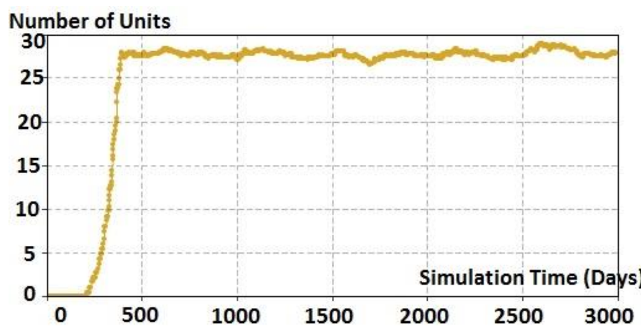


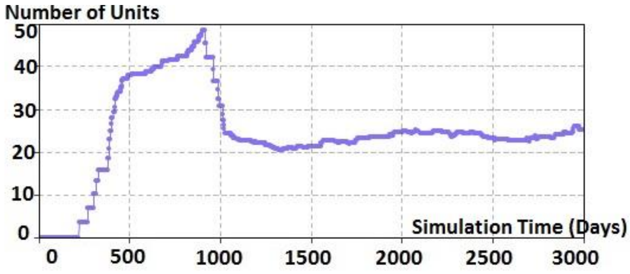
Figure 3. Manufacturer's inventory level in classic supply chain

A sensitivity analysis has been done on the number of retailers in AM supply chain. It should be noted that retailers have been randomly mapped in the system to cover the closest market. Table 3 represents the results.

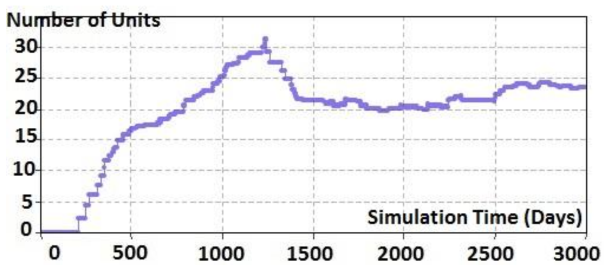
Table 3. Impact of the number of retailers on lead time

Number Of Retailers	Lead Time (days)
2	4.969
5	4.955
7	5.783
9	5.3

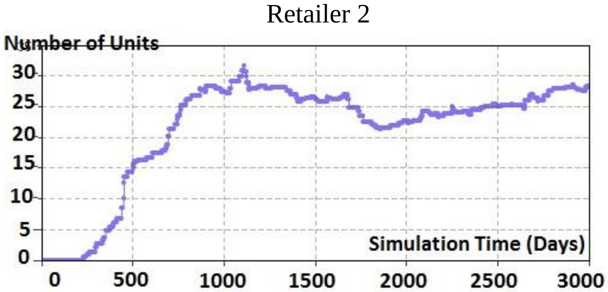
Considering the current parameters of the model (listed in Table 2), the number of retailers does not have a significant impact on improving the lead time. This is due to the fact that suppliers do not face any shortage on materials and also their processing time is relatively fast. However, just the structure of the second scenario reduces the lead time.



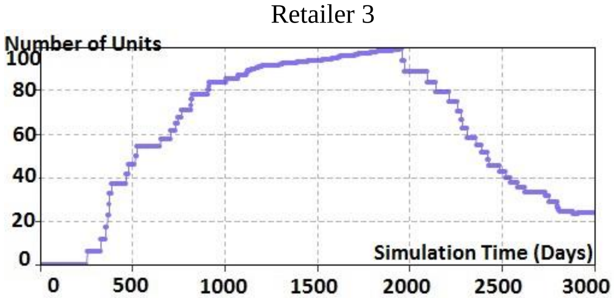
Retailer 1



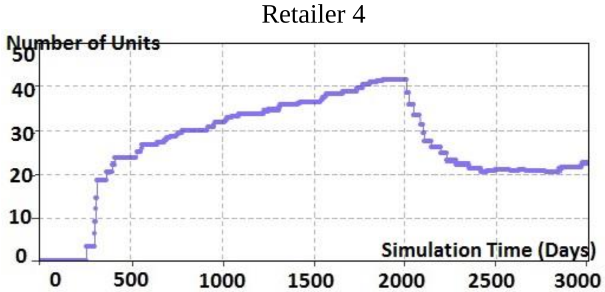
Retailer 2



Retailer 3

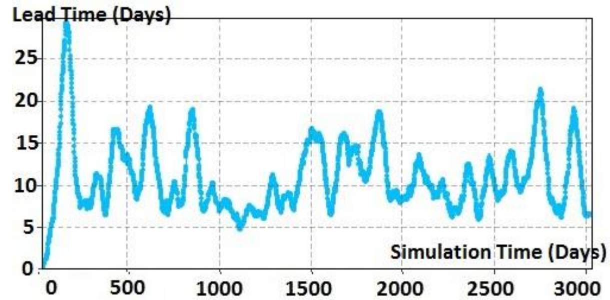


Retailer 4



Retailer 5

Figure 4. Retailers' inventory level in modified supply chain (Retailer 1-5)



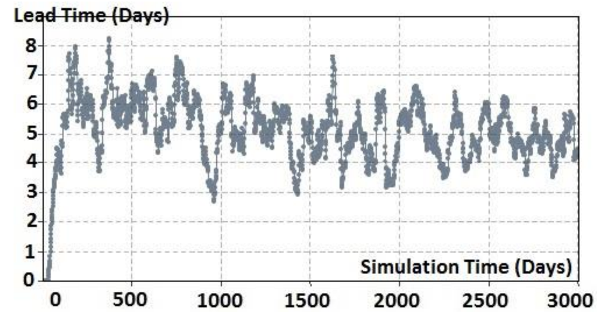


Figure 5. Lead time in the classic supply chain (Scenario 1, top graph) and AM supply chain (Scenario 2, bottom graph)

6.2. Example II: System Dynamics

In this section, we employ system dynamics to study the performance of supply chain. A basic stock and flow diagram representing production-distribution system has been adopted from [34] to show how AM may influence inventory planning in supply chain. The top of the figure is a simple representation of production process (orders flow), while the bottom of the figure maps the distribution process (material flow).

The inflow and outflow variables are the driving forces of the model. These variables are recognized as rate or flow. In addition to flow variables, there are state variables shown by rectangles which are referred to as levels or stocks. The stock variables will change by inflows and outflows. It should be noted that there is a mathematical mapping behind the stock and flow diagram. Figure 6 shows the overall structure of stock and flow diagram. The objective is to study the trend of retailer's inventory over time.

Retailer's inventory is fed by production and is depleted by retailer's sales. Retailer places order to the factory based on their current inventory level ('Retailer Inventory'), their desired inventory level (Target Inventory) and the time in which they want to adjust their inventory to obtain the target inventory. On the other hand, the factory manages their production level based on the 'Order Backlog' fed by retailer's orders and a target production delay represented by 'Production Time' variable. The target production delay is used to help retailers predict the length of the time it takes for their orders to be processed by factory. Although the desired level of production is a function of order backlog and production time, there is some delay in production time influencing the actual production level, so the actual production has been modified using 'Production Adjustment Time' variable. In practical situations, production level cannot easily be changed in real time based on the variations in orders, so the 'production adjustment time' can be defined as a random variable. It is reasonable to assume that production adjustment time is lower in AM-based systems compared to traditional manufacturing systems due to lower tooling and higher automation level.

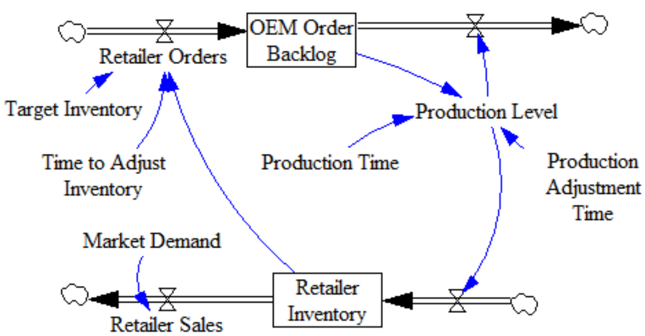


Figure 6. Stock and Flow diagram for retailer's ordering procedure (Modified from [34]).

Figure 7 provides a comparison of the retailer's inventory level in both traditional and AM systems.

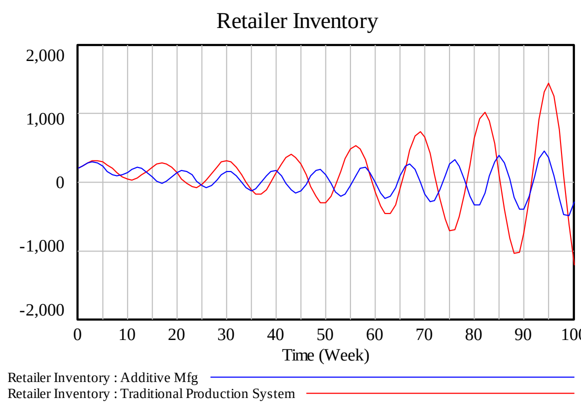


Figure 7. The trend of retailer's inventory over time in both AM and traditional systems (stronger pipeline effect in traditional manufacturing)

As shown, the oscillation in retailer's inventory level is less in AM based system compared to traditional system. This oscillation is due to the delay in receiving orders that the retailer has placed. This oscillation is known as *pipeline effect* in supply chain systems. Therefore, in the current configuration under study, the pipeline effect is stronger in traditional supply chain than AM based supply chain which may result in maintaining higher inventory levels by the manufacturer.

7. CONCLUSION

This paper has briefly traced the transformative effects of additive manufacturing on traditional supply chains. The changes that AM brings to the production systems as well as the resulting business models have been discussed. The potential for using simulation techniques at different decision making levels have been presented. Two examples of agent based simulation and system dynamics have been provided to illustrate how the performance and structure of supply chain may change as a result of AM technology.

Nevertheless, simulation models have their own limitations. Future directions for research include developing new hybrid techniques (e.g. simulation based optimization) to optimize the performance of the system considering different sources of uncertainty. Feeding real world data to the models would improve the accuracy of the results and provide baseline for evaluation. The purpose of analyses provided in this paper was to just study the trend not the exact values of performance indicators (lead time and inventory level). However, simulation models can be extended to provide more accurate information on the system performance and evaluate different policies.

Acknowledgement

This material is based upon work supported by the National Science Foundation under grant # CMMI- 1435908. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

References:

[1] R. W. Appleton, "Additive Manufacturing Overview For The United States Marine Corps," 2014.

[2] "Wohlers Report 2014 Table of Contents." [Online]. Available: http://wohlersassociates.com/2014contents.htm. [Accessed: 02-Sep-2014].

[3] C. L., "Fostering Mainstream Adoption of Industrial 3D Printing: Understanding the Benefits and Promoting Organizational Readiness," Jun. 2014.

[4] J. Holmstrom, J. Partanen, J. Tuomi, and M. Walter, "Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment," *J. Manuf. Technol. Manag.*, vol. 21, no. 6, pp. 687–697, 2010.

[5] S. H. Khajavi, J. Partanen, and J. Holmström, "Additive manufacturing in the spare parts supply chain," *Comput. Ind.*, vol. 65, no. 1, pp. 50–63, Jan. 2014.

[6] D. A. Dornfeld, *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media, 2012, p. 298.

[7] T. A. Campbell and O. S. Ivanova, "Additive Nabufacturing as Disruptive Technology: Implications of Three-Dimensional Printing," *Technol. Innov.*, vol. 15, no. 1, pp. 67–79, Jan. 2013.

[8] "Additive manufacturing: opportunities and constraints c1 Additive manufacturing: opportunities and constraints | Georgy Dzhenzhera - Academia.edu." [Online]. Available: http://www.academia.edu/6451906/Additive_manufacturing_opportunities_and_constraints_c1_Additive_manufacturing_opportunities_and_constraints. [Accessed: 05-Sep-2014].

[9] S. S. Spahi, *Optimizing the Level of Customization for Products in Mass Customization Systems*. ProQuest, 2008, p. 219.

[10] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Springer Science & Business Media, 2009, p. 484.

[11] C. Zhou, Y. Chen, Z. Yang, and B. Khoshnevis, "Development of a multi-material mask-image-projection-based stereolithography for the fabrication of digital materials BT - 22nd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2011, August 8, 2011 - ," 2011, pp. 65–80.

[12] "Could 3D Printing Change the World?" [Online]. Available: http://www.atlanticcouncil.org/publications/reports/could-3d-printing-change-the-world. [Accessed: 05-Sep-2014].

[13] "Additive Manufacturing and the Future of the Supply Chain | Enterra Solutions." [Online]. Available: http://www.enterrasolutions.com/2013/08/additive-manufacturing-and-the-future-of-the-supply-chain.html. [Accessed: 05-Sep-2014].

[14] A. Mina, "Additive Manufacturing: State-of-the-Art, Capabilities, and Sample Applications with Cost Analysis," KTH, 2012.

[15] Y. . Yusuf, M. Sarhadi, and A. Gunasekaran, "Agile manufacturing:," *Int. J. Prod. Econ.*, vol. 62, no. 1–2, pp. 33–43, May 1999.

[16] M. Christopher and L. J. Ryals, "The Supply Chain Becomes the Demand Chain," *J. Bus. Logist.*, vol. 35, no. 1, pp. 29–35, Mar. 2014.

[17] H. J. Ahn and H. Lee, "An Agent-Based Dynamic Information Network for Supply Chain Management," *BT Technol. J.*, vol. 22, no. 2, pp. 18–27, Apr. 2004.

[18] WohlersTerry, "Tracking Global Growth in Industrial-Scale Additive Manufacturing," Mary Ann Liebert, Inc. 140 Huguenot Street, 3rd Floor New Rochelle, NY 10801 USA, Mar. 2014.

[19] M. Christopher and M. Holweg, "'Supply Chain 2.0': managing supply chains in the era of turbulence," *Int. J. Phys. Distrib. Logist. Manag.*, vol. 41, no. 1, pp. 63–82, 2011.

[20] KurmanMelba, "Carrots, Not Sticks: Rethinking Enforcement of Intellectual Property Rights for 3D-Printed Manufacturing," Mar. 2014.

[21] M. T. Melo, S. Nickel, and F. Saldanha-da-Gama, "Facility location and supply chain management - A review," *Eur. J. Oper. Res.*, vol. 196, no. 2, pp. 401–412, 2009.

[22] J. Ding and X. Liu, "Supply chain optimization with deterministic and uncertain demand: A brief review BT - 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce, AIMSEC 2011, August 8, 2011 - August 10, 2011," 2011, pp. 2453–2456.

[23] X. Chen, Y.-S. Ong, P.-S. Tan, N. Zhang, and Z. Li, "Agent-Based Modeling and Simulation for Supply Chain Risk Management - A Survey of the State-of-the-Art," in *2013 IEEE International Conference on Systems, Man, and Cybernetics*, 2013, pp. 1294–1299.

[24] K. Lucas, M. Brooks, A. Darnton, and J. E. Jones, "Promoting pro-environmental behaviour: existing evidence and policy implications," *Environ. Sci. Policy*, vol. 11, no. 5, pp. 456–466, Aug. 2008.

[25] C. M. Macal and M. J. North, "Toward teaching agent-based simulation BT - 2010 43rd Winter Simulation Conference, WSC'10, December 5, 2010 - December 8, 2010," 2010, pp. 268–277.

[26] E. Chattoe, "Why Are We Simulating Anyway? Some Answers from Economics," pp. 78–104, Jan. 1996.

[27] C. M. Macal and M. J. North, "Tutorial on agent-based modelling and simulation," *J. Simul.*, vol. 4, no. 3, pp. 151–162, Sep. 2010.

[28] H. Akkermans and N. Dellaert, "The rediscovery of industrial dynamics: the contribution of system dynamics to supply chain management in a dynamic and fragmented world," *Syst. Dyn. Rev.*, vol. 21, no. 3, pp. 173–186, 2005.

[29] S. M. Disney, "The evolving frontiers of the bullwhip problem," in *EUROMA Annual Conference*, 2005.

[30] P. Georgiadis, D. Vlachos, and E. Iakovou, "A system dynamics modeling framework for the strategic supply chain management of food chains," *J. Food Eng.*, vol. 70, no. 3, pp. 351–364, Oct. 2005.

[31] M. Özbayrak, T. C. Papadopoulou, and M. Akgun, "Systems dynamics modelling of a manufacturing supply chain system," *Simul. Model. Pract. Theory*, vol. 15, no. 10, pp. 1338–1355, Nov. 2007.

[32] B. J. Angerhofer and M. C. Angelides, "System dynamics modelling in supply chain management: research review," in *2000 Winter Simulation Conference Proceedings (Cat. No.00CH37165)*, 2000, vol. 1, pp. 342–351.

[33] J. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, 2000, p. 982.

[34] "System Dynamics Methods: A Quick Introduction." [Online]. Available: http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/SDIntro.htm. [Accessed: 15-Nov-2014].